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13. ABSTRACT (Maximum 200 words)

This research is to develop new techniques in experimental structural dynamics that use a Laser Doppler Vibrometer (LDV) to measure structural vibration. This report discusses use of a fixed laser vibrometer for vibration control experiments and for vibration testing.

The laser vibrometer measures velocity directly with a small time and phase delay. Thus use of the laser as a sensor can improve performance of a control system for vibration suppression. Furthermore, the laser can be moved over the surface of the structure to measure the vibration of many points. Experiments are being performed using the laser to measure vibration, and piezoceramic patch actuators to suppress vibration.

Laser reflection is being investigated as a new way to study the vibration response of structures. This technique is a very simple way to study vibration and control of structures by mapping the operational deflections onto simple line patterns.

The laser is also being used to measure vibration through the glass door of a vacuum oven. The project is to study the effect of high temperatures on piezoceramic materials, structural adhesives, and structural damping treatments. The laser can measure vibration on high temperature surfaces where other sensors would fail.

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FINAL TECHNICAL REPORT FOR THE GRANT No. DAAG55-97-1-0299

NEW TECHNIQUES IN EXPERIMENTAL STRUCTURAL DYNAMICS USING A SCANNING LASER VIBROMETER

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SUMMARY

The objective of this research is to develop new techniques in experimental structural dynamics for use with a laser vibrometer. The laser system was purchased partly from an equipment grant from the ARO. Ordering and getting the equipment operational took one half year, and the equipment has had about seven months use at the time of writing this report. All the equipment requested in the revised proposal was purchased. The only change from the original budget is that the price on one item decreased, and the additional money was used to purchase extra software. The equipment consists of a fixed reference laser, options for a scanning laser vibrometer that A&T has from another grant, and associated testing equipment. A Laser Vibrometry Laboratory was established at A&T University for use of the new equipment.

Thus far, the fixed laser has been used on vibration control experiments and for vibration testing. The other equipment has been used for structural health monitoring and modal analysis research, an undergraduate teaching experiment, and a graduate course project. The laser equipment helped the PI of this project to get two new small grants from United Technologies Research Center and Sandia National Laboratories, both involving use of the associated equipment purchased from this grant. The different research uses of the laser are discussed in this report.

The laser system is also helping to attract more students to come to A&T and to perform research in the Structural Dynamics Laboratory. Prospective students have toured the Laser Vibrometry Laboratory at A&T and are impressed with the research equipment available. An American Society of Mechanical Engineers tour was also given of the Laser Vibrometry Laboratory. About twenty engineers from local industry saw a demonstration on use of the laser. A number of faculty visitors have also seen the laser laboratory. An article on the laser award was also published in the Greensboro News and Record newspaper. The ARO grant to purchase the laser system is a benefit to A&T university, the students, faculty, and the community.

1. STATEMENT OF THE PROBLEM

The objective of this research is to develop new techniques in experimental structural dynamics that can take advantage of the use of a Laser Doppler Vibrometer (LDV) to measure structural vibration. This report will discuss use of a fixed laser vibrometer as that was the main equipment item obtained through this grant.

Active damping using velocity feedback is often the most effective method to suppress vibration of structures with moderately wide band excitation [1]. This is because at resonance the structural velocity is in phase with the excitation force and the vibration amplitude is only limited by the damping of the structure. For a sinusoidal excitation, position feedback can be used to move the structural frequency away from resonance, however, this type of control law would become complex for moderately wide band inputs. Also, changing the structural frequencies requires large control forces. Thus, efficient and simple control laws can be derived using velocity feedback. However, velocity feedback is difficult to obtain because it requires integrating an accelerometer signal or differentiating the strain signal from a Lead Zirconate Titanate (PZT) patch. This causes time delay in the control circuit and differentiation puts high-

frequency noise into the control circuit that must be filtered out, causing more time delay. Time or phase delay reduces performance and can destabilize the structure.

The laser measures velocity directly with a small time and phase delay. Thus use of the laser as a sensor can potentially improve performance of a control system for vibration suppression. Furthermore, since the laser measurement is fast, the laser can potentially be moved over the surface of the structure to measure the vibration of many points. With more measurement points, the performance and stability robustness of the controlled structure increases. The use of the laser as a vibration sensor for control is the primary research done thus far with the equipment.

The laser can also be used as a new way to study the vibration response of structures. The technique being developed at A&T is called Vibration Imaging using Laser Reflection, and is discussed in this report. The laser also can measure through glass and projects are underway to use the laser to measure flutter vibration through the glass side of a wind tunnel, and to measure vibration through the glass door of a vacuum oven. The oven project is to study the effect of high temperatures on PZT materials, structural adhesives, and structural damping treatments.

2. SUMMARY OF RESULTS

The main results are that the laser has been used as a sensor for low frequency vibration suppression, and to study vibration images of bending-torsion coupling of a model wing structure.

3. PUBLICATIONS

Publications related to this grant are listed below.

1. Li, J., Schulz, M.J., Naser, A.H., Pai, P.F., and Chung, J.H., "Damage Detection on an Aircraft Wing Panel using Vibration Measurements," submitted to the ICAST'98 conference, 14-16 October 1998, Cambridge, MA, abstract accepted.

2. Schulz, M.J., Wheater, E.A., Pai, P.F., "Structural Damage Detection Using a Laser Vibrometer and Piezoceramic Patches," submitted to the IMAC-XXVII conference in Orlando, Fla., February 8-11, 1999, abstract in review.

3. Wheater, E.A., Schulz, M.J., Naser, A.S., Waldron, K.W., and Pai, P.F., *"Active Vibration Control of Flexible Structures using Piezoceramic Patches and a Laser Vibrometer,"* 5th International Conference on Composites Engineering, July 5-11, 1998, Las Vegas, Nevada.

4. PERSONNEL

The personnel at NCA&TSU that participated in research using equipment from this grant are listed below.

1. Mark J. Schulz, Assistant Professor
2. P. Frank Pai, Assistant Professor
3. Ahmad S. Naser, Adjunct Assistant Professor
4. Eric A. Wheater, Ph.D. student

5. BILBLIOGRPHY

1. Schulz, M.J., and Inman, D.J., *"Eigenstructure Assignment and Controller Optimization for Mechanical Systems,"* IEEE Transactions on Control Systems Technology, (2), No. 2, June 1994.

6. EQUIPMENT ACQUIRED

The cost for the requested equipment is given in Table 1. This is based on the revised lower cost budget submitted.

Table 1. Scanning Laser Vibrometer equipment purchased

ITEM (Manufacturer)	DESCRIPTION	COST
OFV-3001-S (Polytec PI)	Single point reference laser	49000
PSV-Z-069-U (Poltyec PI)	Desk-top software for PC	3250
PSV-CRT-200 (Polytec PI)	Mobile Industrial Cart	1950
PSV-TT (Polytec PI)	On-site training and set-up	2000
Extended Warranty (Polytec PI)	Scanning laser, years 3 and 4, 4% cost/yr	15684
Extended Warranty (Polytec PI)	Reference laser, years 2-4, 4% cost/yr	5518
Pentium Computers (Gateway 2000)	200 MHz (2), Laptop (1)	14497
Writable CD ROM disks (Global)	ED disks for data transfer,	
PC Printers, laser and color (Global)	HP laserjet 6, HP Deskjet 1600C	3121
Matlab version 5.0 (Math Works)	Software to use with laser	2397
V01824SA Vacuum Oven (Lindberg/Blue)	Oven to test PZTs	10250
777158-01 (National Instruments)	Software to use with laser	466
DP420 Win 200	Software upgrade to windows 95	1850
S9208, four (Physical Acousitcs)	Acoustic emission sensors	3200
Analyzer (Larson Davis)	Acoustic analyzer, microphone	18574
XVS-163-24I-C, etc. (Equipto Electronics)	Electronics cabinet	2372
Security system (Alarmguard Security)	Alarm system for laboratory	1350
	TOTAL	$135,479

7. SUMMARY OF RESEARCH PROJECTS USING EQUIPMENT

The different uses of the laser system are described below. These projects are in the beginning stage regarding use of the laser and are partially supported by the NASA Center for Aerospace Research (CAR) at North Carolina A&T State University, and the Army Research Office (Technical Monitor Dr. Gary Anderson).

7.1 Vibration Suppression using a Laser Vibrometer Sensor

Vibration control is critical for advanced lightweight structures such as helicopters, aircraft wing structures, and space structures. Smart materials such as PZT can provide a reliable means to reduce vibration for these applications. Active damping using velocity feedback is a practical control method to suppress vibration because it is simple and requires low control forces. This project uses PZT patches for actuators and a laser vibrometer as the velocity sensor to form an active vibration suppression system.

A laser vibrometer is useful as a velocity sensor because no integration or differentiation of the control signal is required, the vibration normal to the surface of the structure is measured, no wires are needed, the sensor is non-contact, and the sensor can be moved over the surface of the structure. In Figure 1 the fixed laser and two PZT patches are used to control the free vibration of an aluminum cantilever beam. Figure 2 shows the improvement in the transient response due to the control using two PZT patches at the root of the beam and the fixed laser sensing the vibration near the free end.

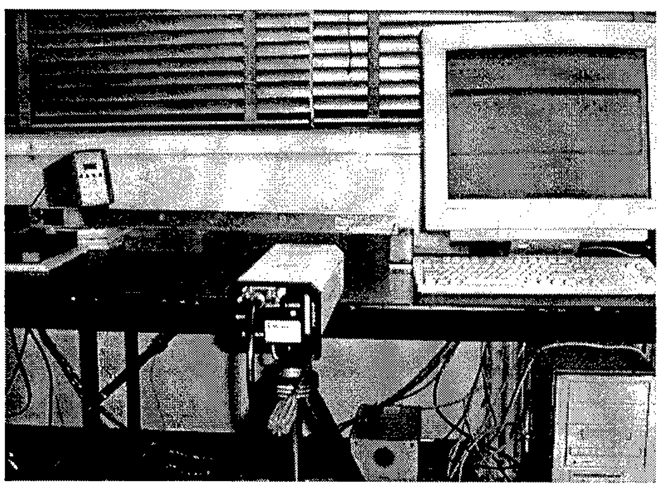
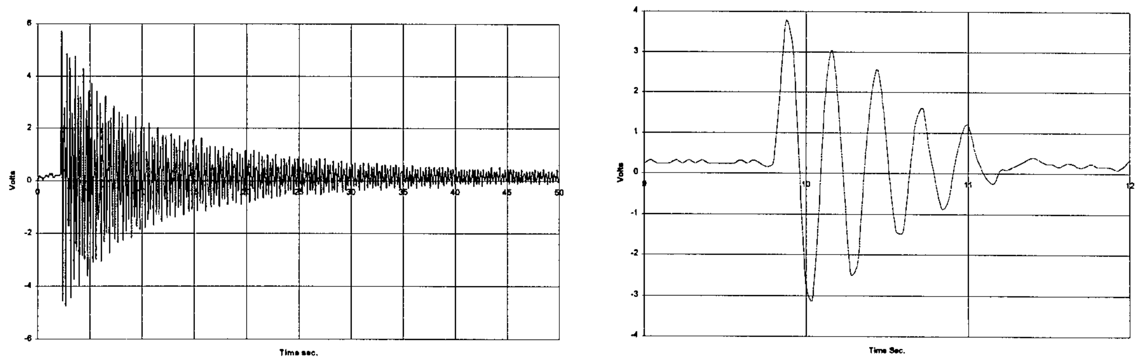


Figure 1. Cantilever beam, fixed laser, and dSpace experimental apparatus



(a) open loop (b) closed loop

Figure 2. Transient response of cantilever beam

The control using the fixed laser was successful, but if the laser could be scanned over the surface of a structure, control of the higher modes can be achieved. An oscillating mirror scanner using a piezoceramic bimorph actuator is shown in Figure 3. This was designed by an A&T student to scan a laser beam over the surface of a structure. In the design it was important to have the lowest vibration mode above 30Hz.

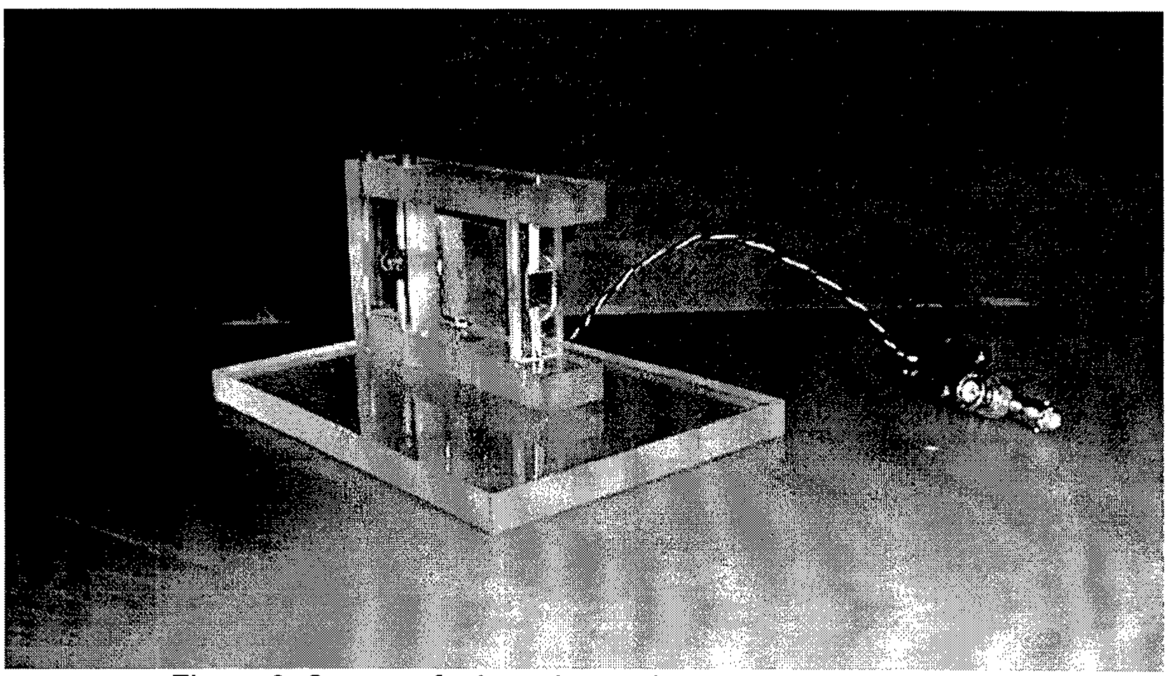


Figure 3. Scanner for laser beam designed by A&T student

The laser beam scanner is used in a control loop shown in Figure 4. The laser beam is scanned to measure vibration along the length of the cantilever beam. A low frequency control loop produced the controlled response shown in Figure 5.

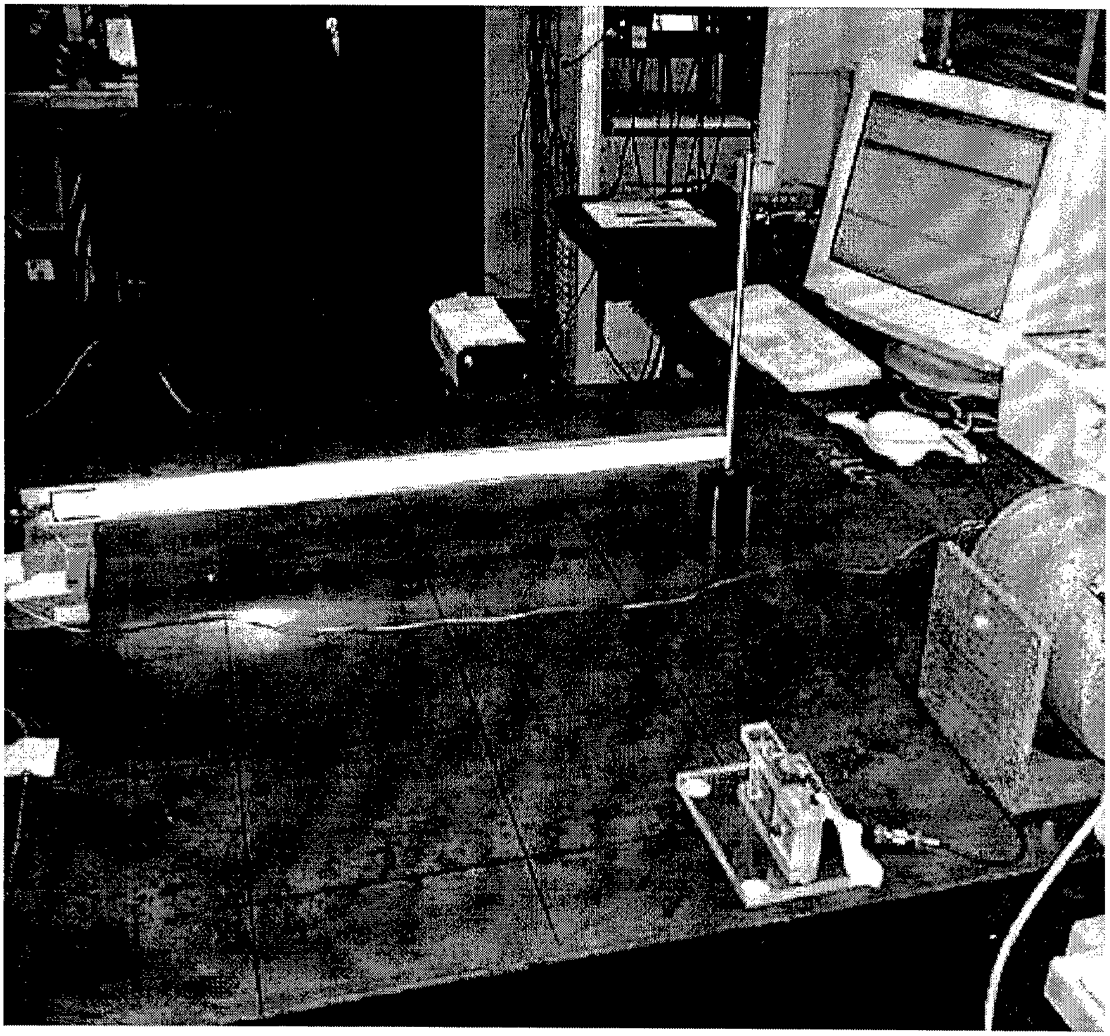


Figure 4. Laser scanning control system

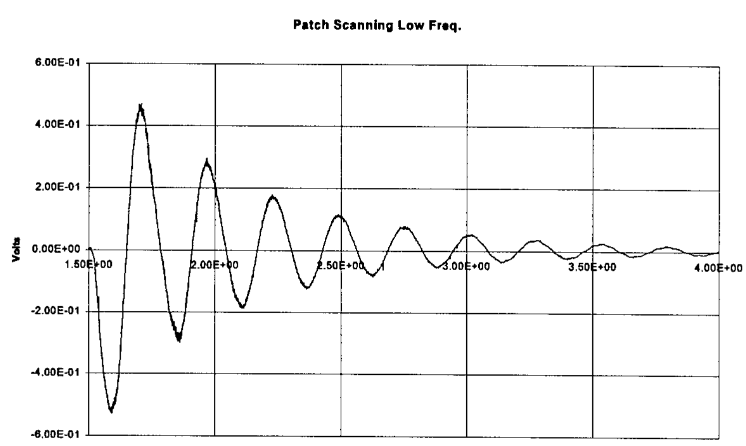


Figure 5. Controlled response of cantilever beam using laser scanning

The technique of scanning the laser has difficulties with speckle and mechanical noise, and an optimum control law has not been derived for this type of sensing. Research is continuing to develop the technique for high frequency scanning. If this can be achieved, large performance gains may be possible and have been predicted by computer simulations.

7.2 Vibration Testing of a Model Wing

Testing of a model wing using a Scanning Laser Doppler Vibrometer (SLDV) is show in Figure 6. The vibration mode shapes of the wing with PZT patches not activated are computed to understand the bending and bending-torsion behavior. The mode shapes are shown in Figure 7. Note the bending-torsion coupling of the third mode.

A new technique being developed at A&T is vibration imaging by laser reflection. The approach places a small mirror or mirror tape on critical sections of a structure and reflects a laser beam off the mirror onto a flat surface. The resulting line patters illustrate the vibration motion of the structure at the mirror location. An example of bending-torsion coupling corresponding to the third mode shape in Figure 7 is shown in Figure 8. This technique is a very simple way to study vibration and control of structures as it maps the operational vibration characteristics onto simple line patterns.

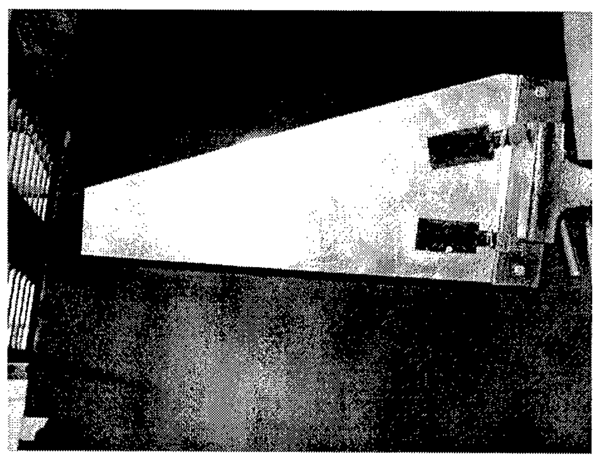


Figure 6. Aircraft model wing with actuators

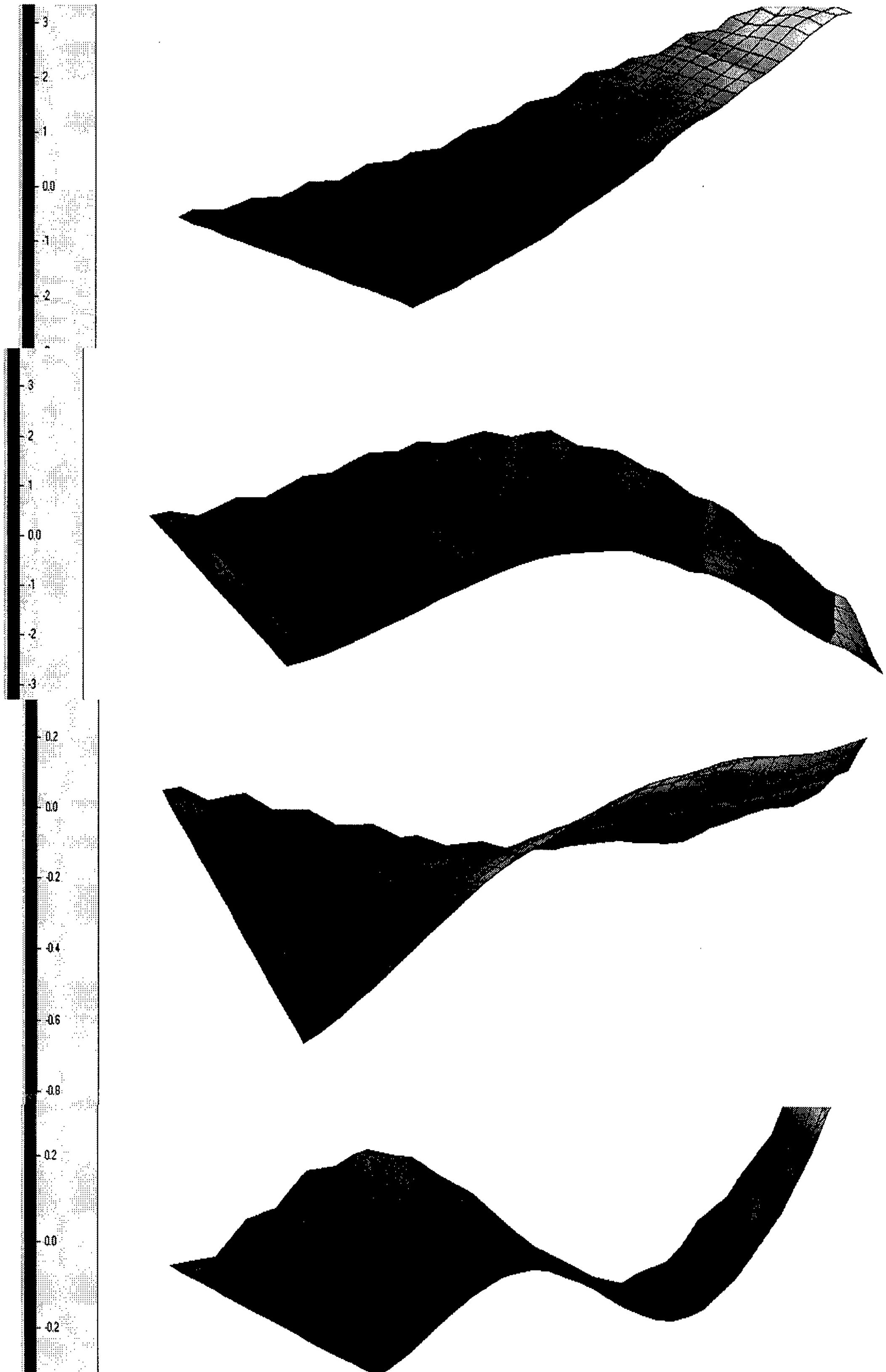


Figure 7. Vibration mode shapes of wing model (1-18Hz, 2-90Hz, 3-120Hz, 4-225Hz)

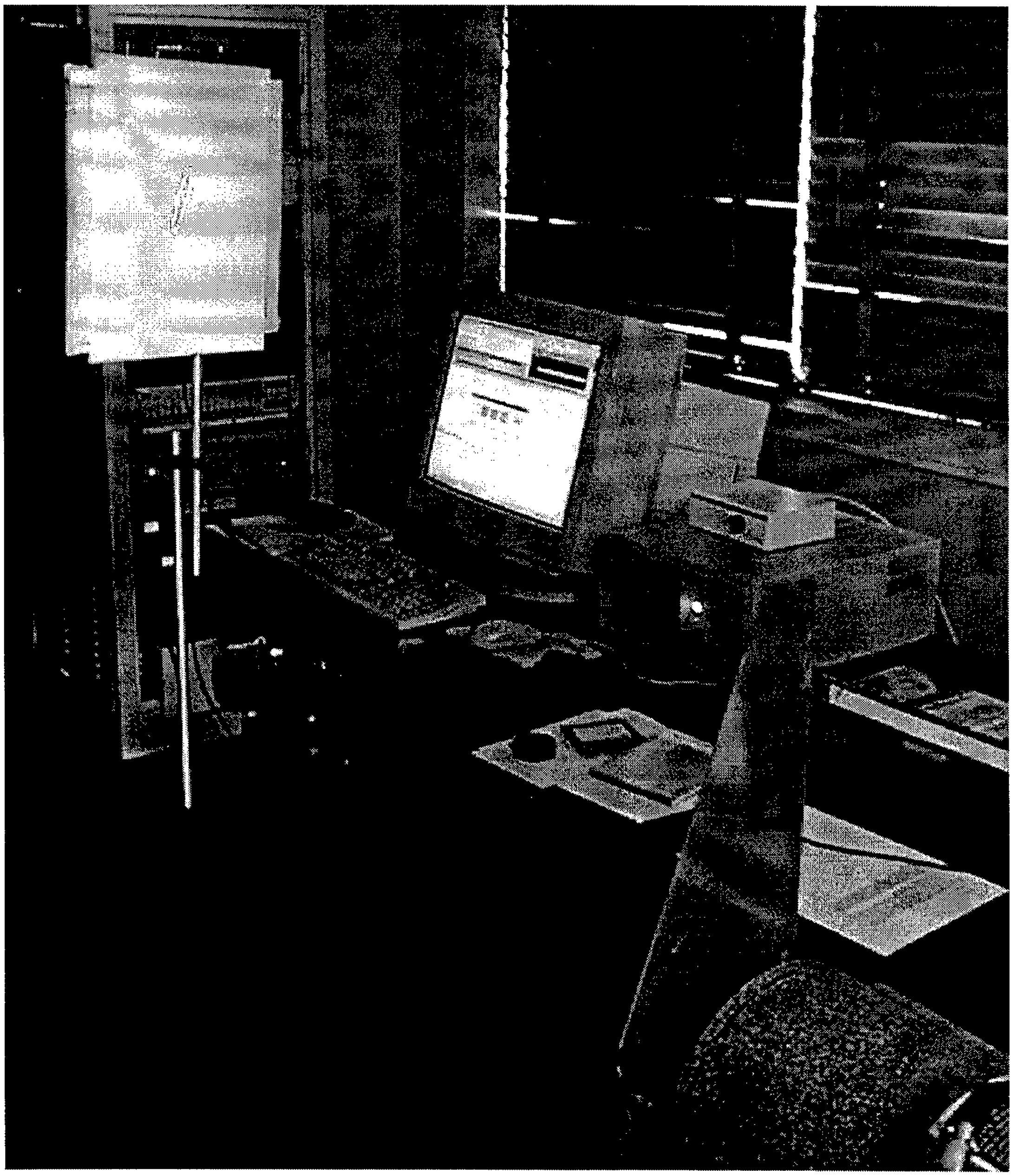


Figure 8. Projected elliptical line pattern of vibrating wing model

7.3 Flutter Suppression of a Model Wing

The PZT patches will be used to control the vibration of the wing in a wind tunnel. The laser pass through a Plexiglas wall in the tunnel as shown in Figure 9.

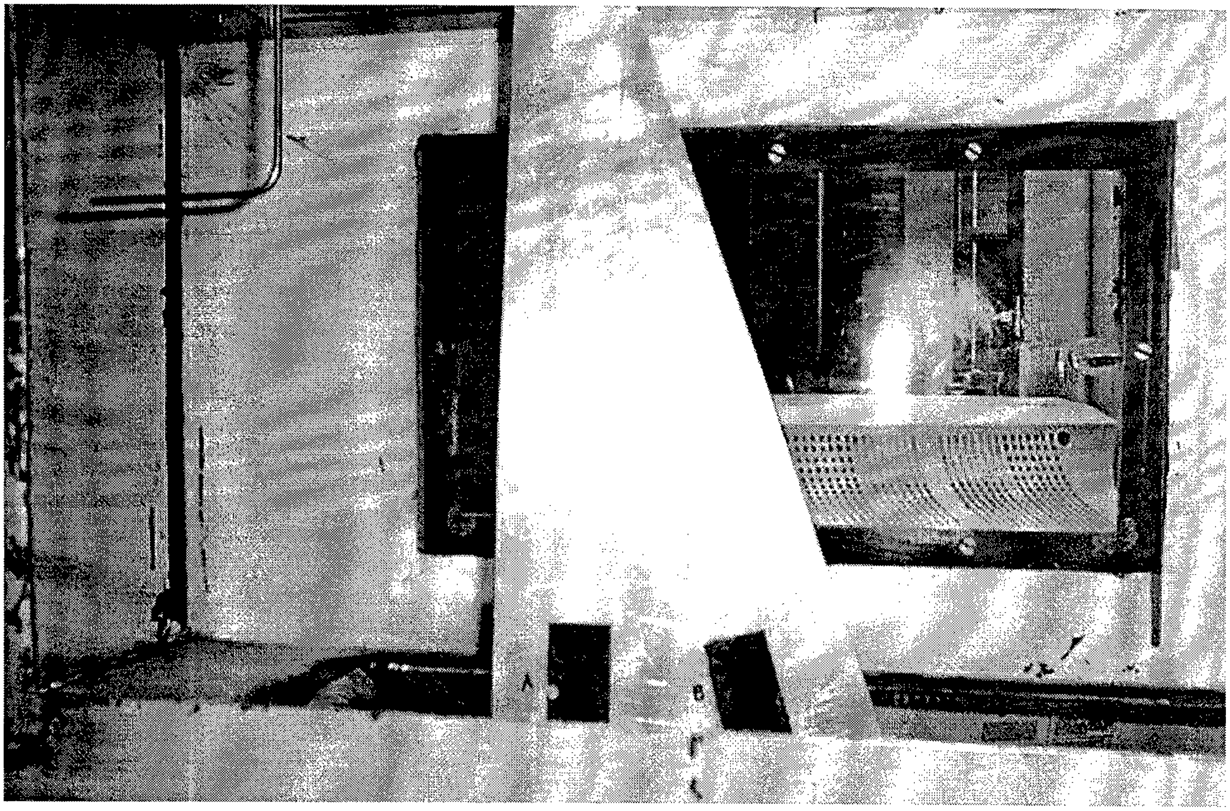


Figure 9. Wing model testing in wind tunnel

7.4 High-Temperature Tesing of PZT Patches and Structural Adhesives

In this experiment, PZT patches are being tested at high temperatures to investigate failure of the structural adhesive, depoling, and elasticity of the bond. The laser will go through a Plexiglas wall in the oven as shown in Figure 10. In Figure 10 the laser is operating through the plexiglas onto a mirror inside the oven and is measuring the vibration of the free end of the cantilever beam shown. The laser can measure vibration on high temperature surfaces where other sensors would fail.

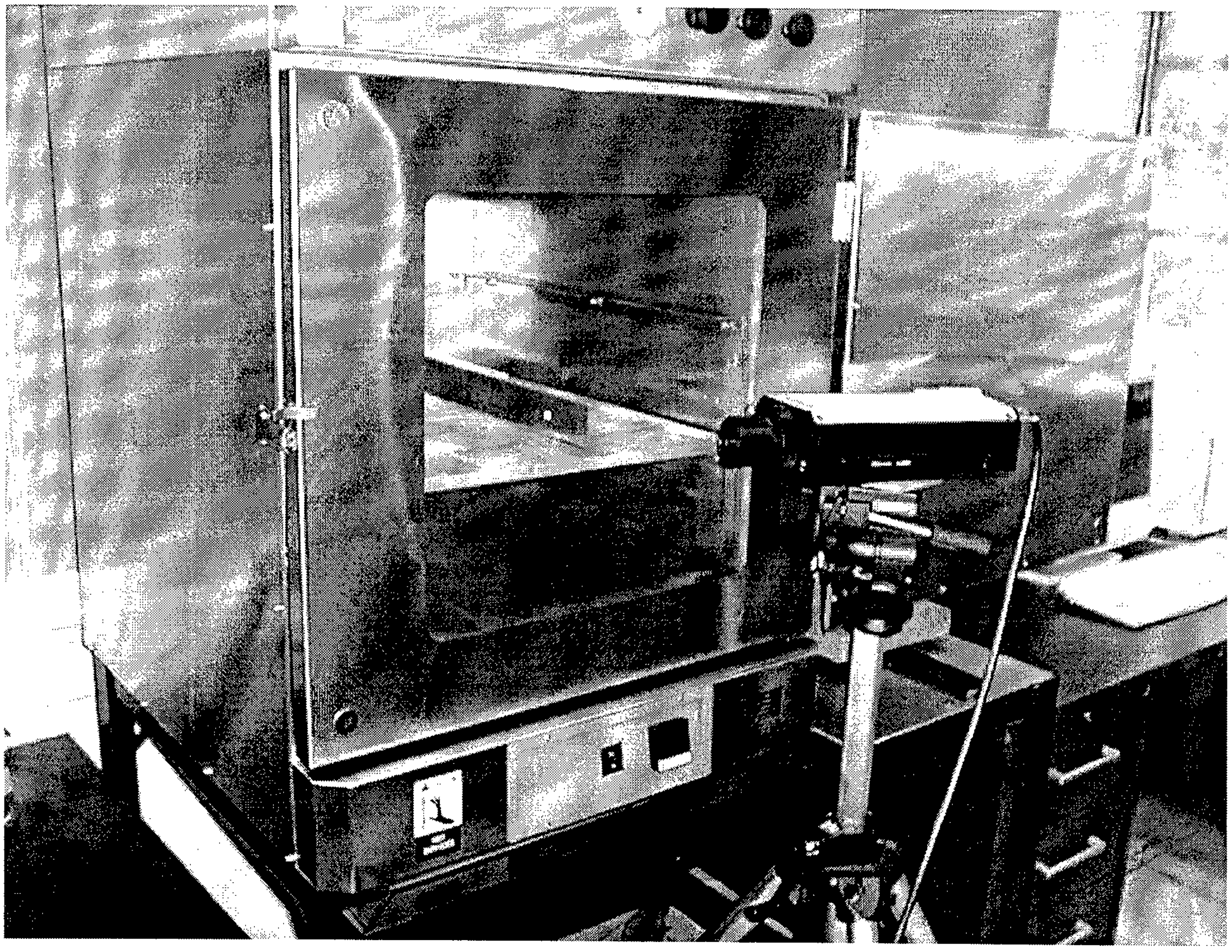


Figure 10. High-temperature testing in a vacuum oven using a laser vibrometer

8. CONCLUSIONS

New techniques using the laser are being developed for vibration and flutter control of flexible structures, and to study the vibration patterns of structures. When fully developed, these techniques may have significant and practical applications to the DoD.

The ARO grant for the laser system has increased research funding at A&T, increased student participation in research, promoted research collaboration with industry and a national laboratory, and increased recognition for university research within the community. The grant from the ARO is sincerely appreciated by the faculty and students at A&T university.